A Water Budget for the Belle Meade and Collier-Seminole Watersheds Using a Spatially Explicit Dynamic GIS Simulation

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This dynamic watershed stormwater model deals exclusively with the short term fate of rain on the land surface during and immediately following a storm. Models like these are helpful in calculating water budgets for watersheds and can be used to create master plans for development attempting to maintain natural flows to estuaries. Flow models using GIS algebra have high spatial accuracy, use actual physical parameters to determine flow links, and eliminate use of empirically and theoretically derived runoff coefficients from dissimilar geographic regions.

This model calculates overland flow, or runoff, reaching the estuary and the amount of water directly absorbed into the soil during a storm. From these results, evaporation, evapotranspiration and baseflow through soil can be estimated. This model does not deal with the final fate of baseflow into canals and creeks, or the flows from these canals and creeks into the estuary. Given time and computer memory, this model could be run for every rain event recorded for a watershed and yearly freshwater loading from non-point source runoff could be determined with a high level of accuracy. The model stores antecedent moisture records important for evaluating rainy season stormwater fates when rain falls everyday for several weeks in a row.

For this study, several sample storms have been simulated and results extrapolated for a water budget for the combined Belle Meade and Collier-Seminole watersheds, including the areas below the Tamiami Trail not typically included in these watershed boundaries.

METHODS

Simulations

This model used a method called mass balancing to determine flows into and out of individual cells in the watershed maps. When rain falls on any given cell, it does one of several things: percolates into the soil, ponds on top of the soil in very flat and windless areas, or moves away from the cell along a slope. This model used GIS algebraic functions to effectively pour water into a cell, determined how much remained in the cell based on available soil and retention area capacity, and then used another set of trigonometric functions to determine the direction the remaining rain flow.

When a given cell's soil capacity was full or the infiltration rate exceeded, the water either remained as surface water in that cell or moved proportionately into adjacent cells. The same calculations began again for the next set of cells, combining the rain falling directly onto the cell with the runoff from any adjacent cell or cells. This iteration was continued until all runoff reached the estuary boundaries. The watershed was assumed to end at areas of contiguous saltmarsh or mangrove.

The amount of rain that moved into the soil was determined by the soil type in that particular cell. Each soil type has a range of permeability determined by the Natural Resources Conservation Service (NRCS) that are given in inches per hour. Each soil type is also characterized by the amount of void space available for water. This capacity has also been determined by the NRCS and is given in units of inches per inch, or in other words, for every inch in a soil column of unit size, this is the fraction that can hold water under normal moisture conditions.

All soil parameters were chosen from those listed for the top 12 inches of each soil type and the average between minimum and maximum used for calculations. Total capacity was calculated as the length of the soil column with greater than 0.2 in/hr permeability. Evaporation, evapotranspiration and downward soil flux were assumed negligible during the storm event, and were then estimated on a daily basis following the storm event. Evaporation and evapotranspiration calculations use seasonal area averages (Table 1). Soil flux was not estimated because hydraulic conductivity values and water table data were not available for this area. An average rain intensity of 2.4 inches per hour was used for all simulations (2 year 60-minute precipitation, Frederick, Meyers and Auciello 1977). A water budget was completed for every run.

Table 1: Evaporation and evapotranspiration values, inches per day

Month / Community	Jan	Feb	Mar	Apr	May	June
Wetland	1.1	1.5	1.9	1.4	2.1	5.6
Upland, Et only*	0.007	0.007	0.007	0.007	0.007	0.016
Grass, Et only*	0.01	0.013	0.013	0.09	0.09	0.12
Bare, impervious**	3.5	4.2	5.6	5.4	5.8	5.5
Water	3.5	4.2	5.6	5.4	5.8	5.5

Month / Community	July	Aug	Sep	Oct	Nov	Dec
Wetland	5.2	5.7	5.6	1.8	1.8	1
Upland, Et only*	0.016	0.016	0.012	0.012	0.008	0.007
Grass, Et only*	0.12	0.12	0.09	0.09	0.008	0.01
Bare, impervious**	5.7	5.5	5	4.7	4	3.6
Water	5.7	5.5	5	4.7	4	3.6

Notes: These values were converted to similar units and modified by averaging where appropriate from the following sources: Bidlake et al. 1995, Capece et al. 2000, German 2000, Brown 1984 and Heimberg 1984.

* These ecosystems typically have little standing water. When water is present Et value is added to water evaporation until standing water is evaporated.

** These land covers have negligible transpiration, and therefore exhibit evaporation values at or higher than those from water bodies. For this study, water evaporation values were used.

Simulations were completed in raster mode using MFWorks by Keigan Industries. Maps were gridded at a 250 meter resolution. Scripts for all simulations are provided in Appendix A. Please note that some manual map manipulation was required between scripted simulations to create formats required for MapWorks function restrictions. These manipulations involved splitting maps into zones and did not alter data.

<u>Map Acquisition</u>
Historical 6-inch elevations were kriged by ERIM, Inc. from 1-ft contours developed by the South Florida Water Management District. These do not reflect the raised beds of the Tamiami Trail or the culverts under the Trail. Soil maps from the 1996 NRCS version were altered to reflect historic conditions by replacing man made retention areas with extrapolated soil types. The 6-inch topographical map was altered to reflect current conditions by merging with a map of road beds and culverts. The soil maps were altered to reflect conditions in 2000 by superimposing retention areas and impervious surfaces. All retention areas and canals were assumed to have a 2-ft capacity above existing water with unrestricted permeability. Impervious surfaces were assumed to have no capacity and no permeability. Retention and impervious areas for year 2000 simulations were obtained from classification of digital multispectral imagery flown in October 1999.

RESULTS
This model was used to simulate the following rain events: one inch of rain falling on historical elevation and land use patterns, 1 inch on current elevation and land use, 2.4, 4.8 and 7.2 inches at an average 2-yr rain intensity of 2.4 in/hr (Frederik et al. 1977) on current elevation and land use. Both one-inch events are presented as animations to show changes in flow patterns between the undeveloped landscape and the current landscape (see RBNERR CD). All other events were used only to calculate values for water budget determinations.

Figure 1 illustrates a comparison of water volumes. Historic landscape patterns delivered 65% more water volume to estuaries as overland sheet flow. Current patterns drain stormwater into retention areas. Table 2 presents volume quantities shown in Figure 1. Maps of surface flow channels are presented in Figure 2.

Figure 1: Comparison of water budgets - historical land patterns vs current land patterns

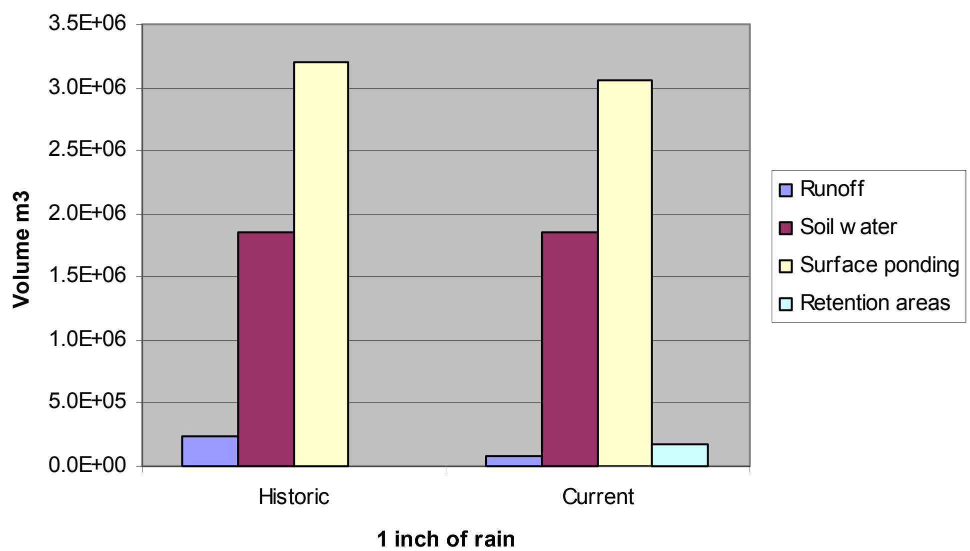


Figure 3 provides water volume data for key water budget storages and flows. As total rainfall increases, soil storage reaches a maximum after about 8 inches of rain, with concomitant increase in surface ponding. The ability of retention areas to contain stormwater does not level off until more than 8 inches of rain. It requires almost 5 inches of rain under current land cover to equal the overland flow to estuaries under historic conditions. A direct comparison between different storage volumes for different rain events is shown in Figure 4.

Table 2: Water budget comparison, historic rain event versus current rain event with 1 inch total rain, Belle Meade and Collier-Seminole watersheds

		Historic, m3	Current, m3
rain		5288461.54	5288461.54
runoff		238595	81384
soilh2o		1846089.74	1854791.67
surface		3203776.71	3178620.87
retention areas		0	173665

Table 3 shows a typical yearly budget. Any rain event below 0.6 inches was considered completely infiltrated during the event. Data used for estimate are included in Appendix B.

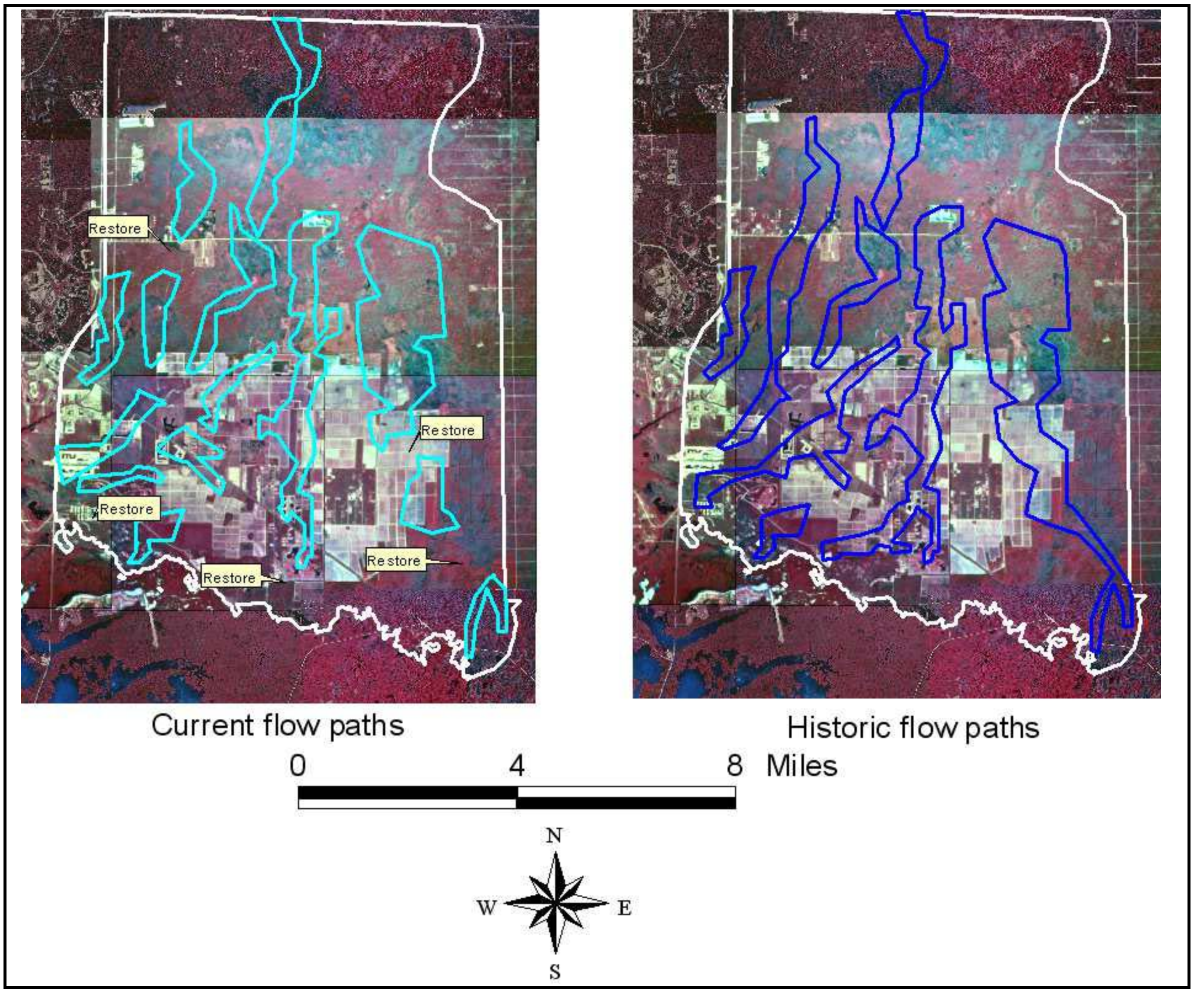


Figure 2. Comparison of changing flowways. Arrows mark discontinuities in current flow paths.

DISCUSSION

The greatest loss in water distribution between historical and current topographic patterns is the amount of runoff reaching the estuary perimeters. About 65% of historic non-point source, or overland sheet flow, is now being retained in the watershed, making it available eventually for lateral flow into canals, but less for freshwater distributed over the entire estuary boundary. This increase in volume available for base flow increases point source freshwater into bays. This change in pattern may conserve the overall amount of water delivered yearly to the estuaries, but it changes the rate and method of delivery. Redirection into retention ponds also increases the water available for evaporation.

Little has changed in the upper reaches of the watershed, but increased impervious surface, retention areas, agricultural canals and Tamiami Trail have changed the flow profile in the lower

Figure 3: Cumulative water budget for average rain intensity
Belle Meade watershed

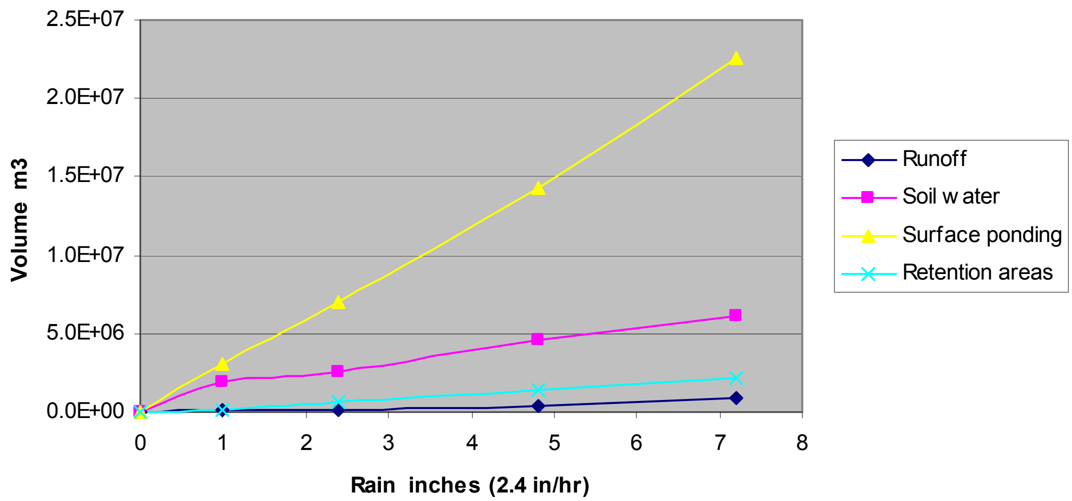
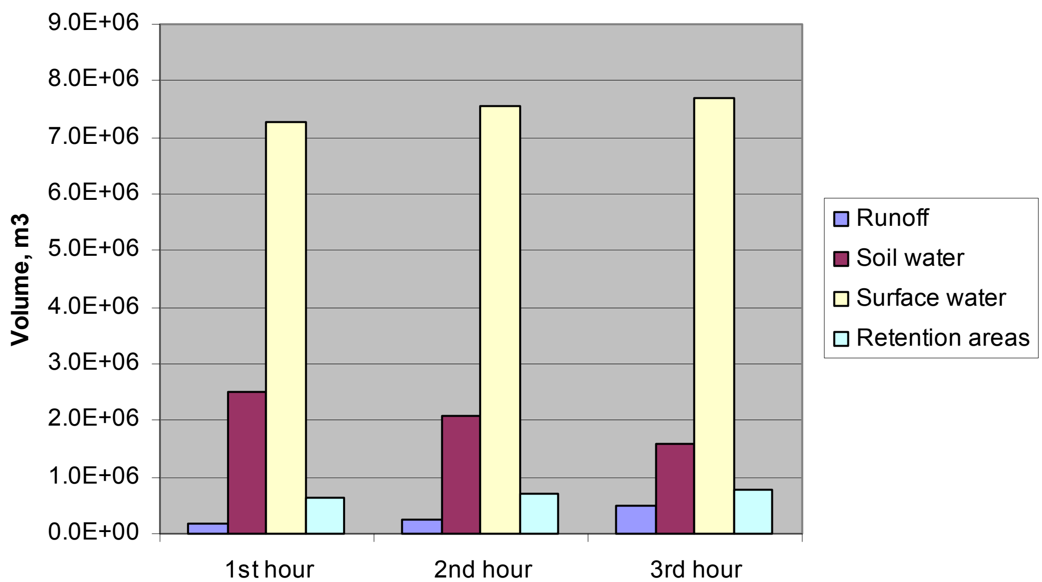


Figure 4: Hourly distribution
2.4 in/hr, 3-hour event



watershed. Maps of channeling differences between historic and current flows illustrate four potential areas of restoration that may recover the distributed overland flow to marsh and mangrove perimeters. Ponding areas north of Tamiami need culverts to move the water into the lower basin, historic flow patterns in the western watershed need to be reconnected, and the flows in the eastern, more agricultural areas need to be widened into a more natural flow way.

Table 3: Water Budget for Belle Meade/Collier-Seminole Basin 1998

Total Rain	50.8	inches
Volume:	2.69E+08	m^3
Soil:	1.34E+08	m^3
Estuary:	3.07E+06	m^3
Surface	3.25E+07	m^3
Evaporation:	9.88E+07	m^3
Available for channel flow:	1.67E+08	m^3

Retention areas in the lower watershed need better connection via spreader canals into the adjacent estuaries. These areas of concern are shown in Figure 2. It is further recommended that historic flow ways remain undeveloped and that retention areas excavated in future developments be more directly connected to flow ways using spreader canals to reduce the amount of point source delivery and increase the amount of distributed overland flow.

REFERENCES

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APPENDIX A

MFWorks Scripts for stormwater overland sheet flow

[this code determines amount of infiltration during first hour of average one-hour intensity and creates two sets of maps – one of the actual runoff paths with volume and the other the amount of moisture in the soil immediately following rain]

```
runt1 = rain2plus - permeab;
          runt2 = runt1 >= Map0;
          run1int = runt1 * runt2;
          run1t = float (run1int);

perc1in = rain2plus - run1t;
save perc1in;

capt1= available - perc1in;
          runt3 = capt1 < Map0;
          runt4int = abs(capt1) * runt3;
          runt4 = float(runt4int);
          capt2= capt1 >= Map0;
          avail2int = capt1 * capt2;
          avail1in = float(avail2int);
Save avail1in;
          run1in  = run1t + runt4;
Save run1in;
          soil1in = perc1in - runt4;
Save soil1in;

drain1 = DRAIN run1 over DEM250;
anim1 =recode drain1 Assigning void to 0
CarryOver;
save anim1;

capt1_2 = avail1in - drain1;
          runt1_2 = capt1_2 < Map0;
          run2t1_2 = ABS(capt1_2) * runt1_2;
          run3t1_2 = float(run2t1_2);
          cap1_2 = capt1_2 >= Map0;
          availt1_2 = capt1_2 * cap1_2;
          avail1_2 = float(availt1_2);
save avail1_2;
          run1_2 = run2 + run3t1_2;

drain1_2 = drain run1_2 over DEM250;

anim2= recode drain1_2 Assigning void to 0
CarryOver;
save anim2;
```

[*Continue this code until lower boundary; then use the code below to make a single antecedent soil moisture map for the remainder of the budget determination*]

```
estuaryt1 = spread c_78 to 1;

estuaryt2 = recode estuaryt1
assigning void to 0
carryover;

estuaryt3=spread estuaryt2 to 1;

estuaryh2o = cover c_78 with estuaryt3;

retentionh2o = cover c_78 with retentionmask;

soilh2o = available - avail1_78;
```

[complete another set of runoff computations if completing a 2-hour or higher storm; then switch to a 24 hour increment and subtract evapotranspiration and soil flux as appropriate to determine water budget between rain events]

APPENDIX B

Rain and extrapolated rain event data used for annual water budgets. Rain data taken from 951EXT-R guage for 1998. All daily rain less than 0.7 inches assumed as total soil infiltration. All others categorized into specified ranges. All percentages determined from GIS simulation for similar rain events.

Rain<.6"		inches	m3				
Automatic soil:		14.75	7.80E+07				
		inches	m3	soil	runoff	surface	retention
Other Rain	1" range	19.31	1.02E+08	3.58E+07	1.53E+06	6.14E+07	3.37E+06
	range2	12.38	6.55E+07	1.55E+07	1.09E+06	4.49E+07	3.99E+06
	range 3	4.36	2.31E+07	4.98E+06	4.47E+05	1.61E+07	1.48E+06
	range 4	0	0.00E+00	0	0	0	0
		50.8	2.69E+08	1.34E+08	3.07E+06	1.22E+08	8.84E+06

Notes	Percentages for incremental rainfall					
	rain inches	range	soil	runoff	surface	retention
	1	0.7-1.7	0.351	0.015	0.601	0.033
	2.4	1.7-3.6	0.236	0.0167	0.686	0.061
	4.8	3.6-6	0.216	0.0194	0.7	0.064
	7.2	6+	0.195	0.029	0.71	0.067
Notes	% Evaporation of surface and retention in June					
	rain inches					
	1	1				
	2.4	0.968				
	4.8	0.966				
	7.2	0.966				
Notes	Monthly conversions for evaporation					
	J	0.636364		A	1	
	F	0.763636		S	0.909091	
	M	1.018182		O	0.854545	
	A	0.981818		N	0.727273	
	M	1.054545		D	0.654545	
	July	1.036364				

Subject to evaporation	1" range	range2	range 3	subtotals 3300 m3
J	0.76	0	0	491.3869
F	1.97	3.83	0	5029.708
M	2.15	1.97	0	4625.368
A	0	0	0	0
M	1.09	0	0	1167.875
June	1.41	0	0	1432.596
July	2.63	2.82	0	6267.941
A	2.84	1.99	0	5267.772
S	3.61	1.77	0	3401.33
O	1.19	0	0	1033.206
N	1.66	0	4.36	1226.62
D	0	0	0	0
	19.31	12.38	4.36	
	36.05			
		Total evaporation:		98814552